# Stable oscillating nonlinear beams in square-wave-biased-photorefractives

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We demonstrate experimentally that in a centrosymmetric paraelectric non-stationary boundary conditions can dynamically halt the intrinsic instability of quasi-steady-state photorefractive self-trapping, driving beam evolution into a stable oscillating two-soliton-state configuration.

The propagation of light in a photorefractive crystal gives rise to intense beam self-action that, in its most generic manifestation, causes fanning and anisotropic scattering [1]. The application of an external bias field to the crystal can drastically change this behaviour, and allow spatial self-trapping and soliton formation: the non-diffracting propagation of micron-sized optical beams [2]. In a biased system this occurs only in a transient regime, for a finite time window, and the resulting nonlinear waves are called quasi-steady-state-solitons [3]. By increasing the natural dark conductivity, this regime can be made stable, giving rise to steady-state screening solitons [4].

In this paper we investigate, for the first time, a fundamentally different stabilization process connected to beam behaviour in a non-stationary external bias field [5]. In particular, we study beam evolution in the presence of an alternating field in centrosymmetric potassium-lithium-tantalate-niobate (KLTN) [6], a material known to support a rich variety of nonlinear beam phenomena [7] [8] [9] [10].

Results indicate that, for appropriate conditions, the beam self-trapping process, that leads to transient quasi-steady-state solitons for stationary conditions, can be driven into a stable self-trapped regime, formed by an alternating oscillation between two beam trajectories, in the *absence* of enhanced dark conductivity. This phenomenon, in our understanding, is made possible by the fact that single optical trajectories, corresponding to the two alternate states of the bias field, non-coincident due to asymmetric diffusion-seeded bending and electro-optic read-out effects, engender the simultaneous formation, through the quadratic electro-optic response of the crystal in the paraelectric phase, of two trapping index patterns, that form two back-to-back specular double layers of charge that halt runaways charge buildup.

Experiments are carried out in samples of zero-cut centrosymmetric photorefractive KLTN, a composite perovskite doped with Copper and Vanadium impurities, with a set-up that is similar to those generally used in photorefractive soliton studies [7] [8], apart from the absence of background illumination and the use of an alternating external voltage source. The sample temperature is kept at a given value T by means of a stabilized current controlled Peltier-junction. A $\lambda$=514nm continuous-wave $TEM_{00}$ beam, from an argon-ion laser, is first expanded and then focused onto the input facet of the sample, and launched along the crystal principal axis z. Focusing is obtained either with a cylindrical y-oriented lens, giving rise to a one-dimensional beam confined in the x transverse direction, for investigation of slab-solitons, or a spherical lens for full two-transverse-dimensional (i.e. x and y) investigation of needle-solitons. The electrodes are deposited on the x facets and the source can provide a square-voltage wave-form of variable peak-to-peak amplitude $V_{sq}$ and period $T_{sq}$. Beam dynamics are observed by means of a top-view and a transverse CCD camera.

The main qualitative phenomenology observed is contained in Fig.(1), where the two-branch oscillation along the x-axis is shown. The laser beam is focused by means of an f=150mm cylindrical lens onto the input facet of a $3.7^{(x)}$x$4.7^{(y)}$x$2.4^{(z)}$ mm sample, giving rise to an approximately one-dimensional (transverse dimension x) fundamental Gaussian beam diffracting in the x direction, as the beam evolves along z. The input beam has a full-width-half-maximum (FWHM) of $\simeq 5$ $\mu$m, and diffracts to 44 $\mu$m after propagating 2.4 mm in the sample (n$\simeq$ 2.4) (see Fig.(1(a)-(b)). The beam has a peak intensity $I_p \simeq 3$kW/m$^2$, whereas no background illumination is implemented. In these conditions, but with a stationary bias, quasi-steady-state self-trapping is observed after a response time $\tau_1 \simeq 3$min, for an external voltage on the x electrodes of V=380V. In the oscillating configuration of Fig.(1(c)-(d)), the external square-wave bias voltage has a peak to peak amplitude $V_{sq}$=760V with a period $T_{sq}$= 10 s (i.e., $T_{sq} \ll \tau_1$), the crystal being kept at T=18°C (thus having a relative dielectric constant of $\epsilon_r \approx 11\cdot10^3$). As the external oscillation occurs, the beam undergoes spatial confinement in one direction towards one electrode (Fig.(1c)), and then in the other, towards the opposite electrode (along the transverse x direction) (Fig.(1d)), oscillating between two distinct optical tra-

jectories. The remarkable result is that this stable oscillating regime, which has a buildup transient $\tau_2 \simeq 15$ min considerably longer than $\tau_1$, continues *indefinetly*, and is thus a stable oscillation in which the beam is *continuously* confined, but in *two* distinct alternating trajectories. The switching time $\tau_{sw} \ll T_{sq}$ is associated with the crystal charging time. Apart from this very short interval $\tau_{sw}$, not of photorefractive nature, the beam is continuously *trapped*. The distance between the two trapped beams at the output is $\Delta$x$\simeq$ 30 $\mu$m.

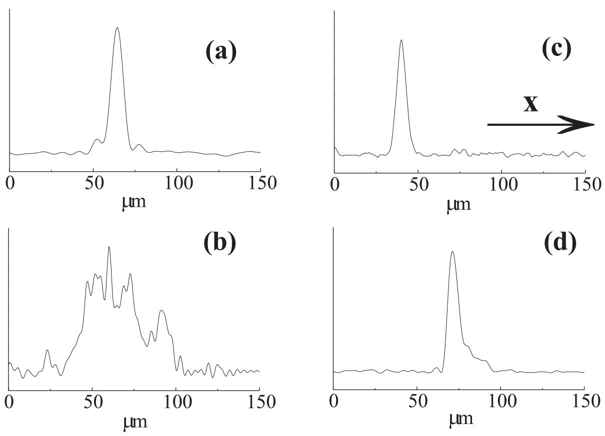


FIG. 1. Stable two-state oscillation of a slab-soliton beam subject to a square-wave bias. (a) Normalized input intensity profile; (b) Output intensity profile after 2.4mm linear propagation in the crystal; (c-d) Output intensity self-trapped profiles of the two alternating states.

An analogous phenomenology is observed for two-dimensional diffracting beams, and is shown in Fig.(2), in a second $2.2^{(x)}$x$2.2^{(y)}$x$6.4^{(z)}$ sample of KLTN, kept at T=26°C ($\epsilon_r \approx 6.5{\cdot}10^3$). Note that the needle confinement extends over approximately 25 diffraction lengths.

As opposed to screening soliton phenomena, we found no strict existence condition associated with the electro-optic response (i.e., $V_{sq}$ and crystal T), much like standard quasi-steady-state self-trapping experiments [3]. The only observable difference in the final oscillating state that depends appreciably on changes in the electro-optic response is the divergence angle of the two trajectories, that gives rise, at the output, to a different value of $\Delta$x. We found that a stronger static polarization induces a stronger divergence.

On the other hand, we observed a distinct dependence of beam evolution on the time scales involved, suggesting that the main underlying mechanism is strongly connected to the temporal oscillations in the boundary conditions. We thus carried out experiments changing the nonlinear time constant, connected to beam peak intensity $I_p$, keeping all other parameters unaltered. Thus, we essentially vary the ratio $T_{sq}/\tau_1$, since $\tau_1$ is approximately proportional to $I_p$. For slow enough dynamics i.e., for $T_{sq}/\tau_1 \ll 1$, the steady oscillating state is *always* reached (at least for the investigated cases), whereas for very rapid dynamics, i.e., for beam intensities such that $T_{sq}/\tau_1 \gg 1$ , single branch evolution is allowed to reach quasi-steady-state destabilization and the steady oscillating situation is not observed. In this case, the beam undergoes a distinctive swinging evolution mimicking the two-state self-trapping of the previous case, as shown in Fig.(3). During one field oscillation, the beam first undergoes self-trapping, deflected in one direction (Fig.(3b)), decays (see Fig.(3a)), diffracting in the forward z direction, and then forms a second transient soliton in the opposite direction (Fig.(3c)), decays again in the z direction, and so forth. Thus, in this case, no *stable* self-trapped oscillating configuration is reached, since most of the time the beam is diffracting ($T_{sq} \gg \tau_1$). Note that the swinging motion is a direct consequence of the residual charge displacement of the previous state, and is much more pronounced than single beam self-bending observed in stationary conditions ($\Delta$x$\simeq$30$\mu$m as compared to $\Delta$x$\simeq$5$\mu$m of conventional self-bending observed).

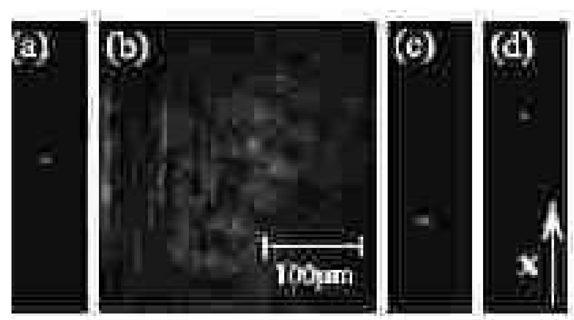


FIG. 2. Stable two-state oscillation of a needle-soliton beam subject to a square-wave of peak to peak amplitude $V_{sq}$=700V, of period $T_{sq}$=10s. (a) Input intensity 6 $\mu$m FWHM distribution; (b) Output intensity 150 $\mu$m distribution after 6.4mm linear propagation in the crystal; (c-d) Output intensity self-trapped profiles of the two alternating states.

We shall limit our discussion to slab-solitons, since understanding of even basic needle soliton phenomenology is still unclear [11]. Concerning the formation of the two-state oscillation, we note that, although in a purely drift-like configuration free photoexcited charge under the influence of a zero average square-wave alternate field $E_{sq}$, with $T_{sq} \ll \tau_1$, cannot give rise to any space-charge separation, asymmetric charge diffusion components can seed two intensity distributions $I_+$ and $I_-$, corresponding to the two alternate states of external field, that separate during propagation along the z axis, and thus allows a non-zero photorefractive response [12]. The final state is a product of beam charge separation during one electric field polarity, combined with electro-holographic effects during the opposite polarity phase [13].

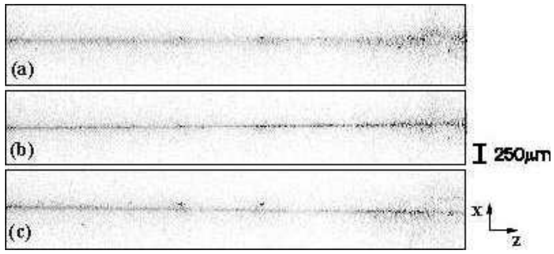


FIG. 3. Soliton swinging: Slab-beam transient dynamics for a $\tau_1 \simeq$2s and $T_{sq}$=10s in a 6.4mm long sample of KLTN, with a $V_{sq}$, sample T=27°C. (a) Top view (y direction) of the diffracting beam, with a 6$\mu$m input FWHM, and linear diffracting 120$\mu$m output; (b)-(c) Two opposite transient self-trapped states.

To break down the process, consider the formation of a single quasi-steady-state soliton with a constant voltage $V=V_+$ (equal to the positive value of the alternating field in the oscillating case)(see Fig.(4a-b)). If we halt beam evolution (attenuating the propagating beam intensity) before the transient trapped regime has decayed (i.e., for t< $\tau_1$), and put V=0, we observe an increased beam diffraction at the output, a signature of the residual defocusing pattern (Fig.(4c)). The diffraction is furthermore slightly asymmetric, as a consequence of the diffusion component in charge separation. If we invert the applied electric field (i.e. $V=V_- \equiv -V_+$), the defocusing pattern is enhanced, and most of the light is diverted to a limited region strongly shifted with respect to the input beam (Fig.(4d)). A wholly specular behaviour is observed when the quasi-steady-state soliton is originally formed with a constant $V=V_-$ (Fig.(4e,f,g, and h)). In the actual alternating field case, since we start from a zero charge separation, and do not allow the system to evolve, if not only partially, during each oscillation ($T_{sq} \ll \tau_1$), the final charge separation and index pattern will be a *symmetric* hybrid combination of the two self-trapped and two deflected beams (see Fig.(4b,d,f,and h)), whereas the actual beam trajectory will switch, following the oscillation of the external field. Note that, during the entire oscillation, the beam continuously maintains its confinement, apart from the small transient $\tau_{sw}$.

Concerning the stability of the nondiffracting pattern, in absence of artificial dark illumination we note that in our case charge separation is intrinsically symmetric. Mobile electrons are forced to drift towards the central region between the two trajectories, forming a potential barrier to further charge separation and saturation, effectively freezing the space-charge structure. The switching, in this case, is only of electro-optic nature, and occurs as a consequence of the electro-holographic read-out of the asymmetric index components in the initial stages of propagation (where the two trajectories are superposed), after the space-charge field has reached a steady-state.

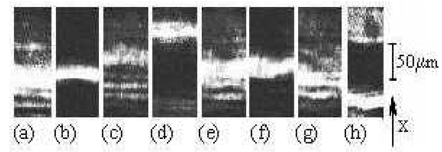


FIG. 4. Break-down of the two-state formation process. Output intensity distribution (conditions of Fig.(1)). (a) Initial output diffraction for V=0; (b) Quasi-steady-state self-trapping for $V=V_+$; (c) Read-out intensity for V=0 (after soliton formation); (d) Read-out intensity for $V=V_-$; (e,f,g,h) specular results starting from $V=V_-$.

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